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Inlet Morpho-Dynamics During a Storm Event Inferred from Tidal Records: A Case Study Of The Brunswick River, NSW, Australia

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Abstract:

A 24.5h moving window is used to analyse storm effects on the tidal dynamics. Compared to earlier studies using window lengths varying between 2h (for tsunami analysis) to 14 days for tidal inlet analysis, the present method provides good resolution of variations of hydraulic efficiency during storms or floods. The importance of de-trending before carrying out the harmonics analysis has been studied and it was found to be highly important. De-trending involved removing the 24.5h mean before harmonic analysis. The main results are the morphodynamic timescale T_{morph} and the varying response functions F_1 and F_2 of the diurnal and semi-diurnal tidal constituents through a storm event at the Brunswick River, Australia.

T_{morph} is inferred from time series of primary semi-diurnal gain $G_2(\mathrm{t})= |F_2|$ with an $\exp(-\mathrm{t}/T_{\mathrm{morph}})$ curve fit. The results show only insignificant morphological change. Thus, the changes in tidal response for this medium sized catchment are mainly due to hydraulic effects. These include the influence of river flow Q_{f} via the non-linear friction term and increased estuary surface area during the flood. The traces of both $F_1(t)$ and $F_2(t)$ in the complex plane show an equilibrium before the storm, dynamic change during the storm and relaxation mimicked by $\exp(-\mathrm{t}/T_{\mathrm{morph}})$ after the storm.

Keywords: Brunswick Heads, morphodynamic timescale, 24.5 hour moving window, morphodynamics, tidal response.

1. Introduction

Tides, waves, freshwater inflow and sediment supply determine the morphology of tidal inlets. Significant changes to one or more of these causes the inlet to move towards a new equilibrium. The time scale at which an inlet responds to such changes is called the morpo-dynamic timescale T_{morph}. The difference between the actual state and the equilibrium state is an exponentially decaying function $e^{-t/T\mathrm{morph}}$ if the rate of change is proportional to the distance from equilibrium. The time constant T_{morph} in the exponential function varies from days to weeks in small systems like Avoca Lake, NSW, AU cf. Thuy et al. (2012) to months for seasonally closing inlets like Thuan An and Tu Hien lagoons on the Central coast of Vietnam, Lam (2009). The recovery time for the coast and river mouths along Miyagi prefecture, Japan after the March 2011 Tsunami ranges from 25 days for the Arahama Coast to 75days for the Akaiko Coast, or 180 days for the Nanakita River, depending on sediment supply (Hitoshi, 2012). T_{morph} can also be as long as 350years for Dollard's tidal flat in The Netherlands, as it responds to slow process of sea level rise (Eysink, 1990).

Morpho-dynamic time scales are usually derived from inlet throat areas and the volumes of flood/ebb tidal deltas, which are costly to measure. The alternative of using process-based morphology models suffers from the lack of real predictive skills of such models. This paper infers hydraulic- and morpho-dynamic changes from tidal records using a 24.5h moving window on the May 2009 storm event Brunswick Heads, Australia.



Figure 1: The Brunswick Heads River entrance with the tide gauge about 630m from the ends of the breakwaters. While the entrance banks (rock walls) are steep, much of the estuary has very flat slopes near MSL.

2. Description of study region and storm event

Brunswick Heads is located at 28°32'17.22"S and 153°33'29.65"E, in northern New South Wales (NSW), Australia (Figure 1). The Brunswick River is a medium sized system with catchment area ca 200km^2, surface area of 3.3km^2 and spring tidal prism 1.94x10^{6}m^3 (Roper et al., 2011). The physical features of the catchment vary from steep, heavily vegetated slopes to open grass flood plain and flat swamp land behind the coastal dunes Webb (1986). The entrance is trained by break waters with the length about 300m. It has a shallow bar fronting the breakwaters which is expected to wash out during major floods. (Hanslow et al, 1996)

The storm considered here occurred between 20/5/2009 and 24/5/2009, however the data analysis period was extended further before and after the event from 15/5/2009 to 5/6/2009 to gain a general view of the hydraulic and morpho-

dynamic processes indicated by the tides. Data kept by the Manly Hydraulics Laboratory, NSW (MHL) is used in this study. Significant wave height H_s, ocean tide at Coffs Harbour, and the water level at the Brunswick Heads River entrance tide gauge (BHTG in Figure 1) during the selected period are presented in Figure 2 and the daily rain fall at Myocum station in the Brunswick River catchment is presented Figure 3.

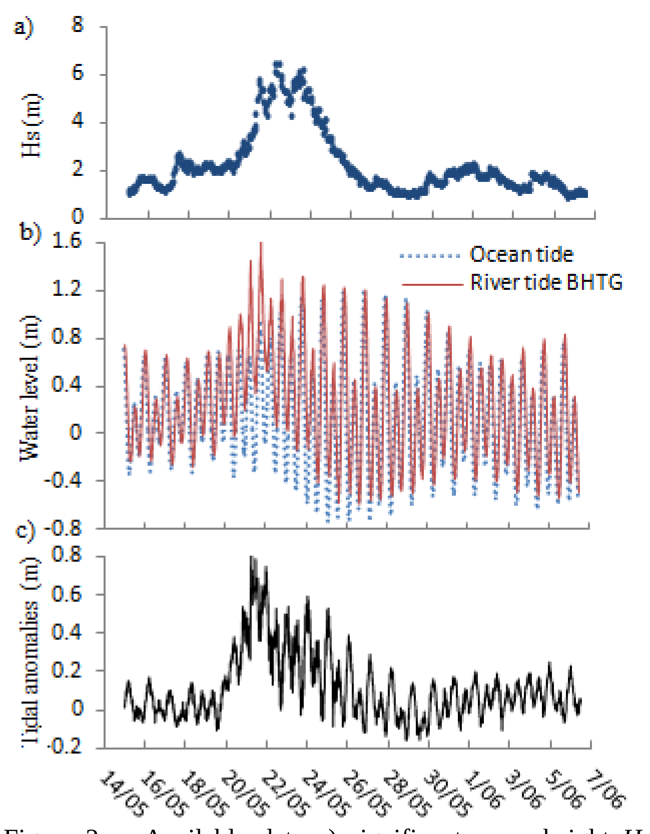


Figure 2: Available data a) significant wave height H_s, b) ocean water levels $\eta_o(t)$ and tidal levels at the BHTG $\eta_r(t)$, c) tidal anomalies at the BHTG from 15/5 to 6/6/2009.

The May 2009 storm event influenced a large area of NSW. This can be seen from increased tidal anomalies at most tidal stations along NSW coast during this time. At Brunswick Heads (BHTG) the highest tidal anomaly was 0.84m observed at 05:45 21/5, 12hours before a peak water level of 1.62m at the BHTG (Figure 2c). The highest significant wave height observed during this event, H_s = 6.5m occurred on 22/5 and H_s > 5m continued from May 21 to May 23 2009 with 12s-13s wave period compared to the normal conditions: H_s = 1.5-2m and T = 8-10s. High waves coinciding with intensive rain fall of nearly 200mm occurred on 21 May, with peak tidal anomalies and peak BHTG water levels observed on that day (Figure 2, 3).

3. Methodology

Tidal records are analysed with a moving window method to obtain the hydraulic parameters and morphology time scales using as described in Thuy et al (2012). A 24.5h window length is chosen so that it is short enough to see the storm induced variations and long enough for reasonable accuracy.

Abe & Ishii (1981) used a similar method with a 2h moving window for studying tsunami travel time, while window lengths of 3 to 14 days were used by Hinwood & McLean (2001) to analyse the response of 5 tidal components for Lake Conjola, AU to inlet morpho-dynamic changes forced by storms, floods and wave-driven inlet closure. Their method had drawbacks related to the stability of tidal coefficients and their longer window of 14 days filtered out the effect of storm- or rainfall events which last only 3-5 days. The 3 day window method, provided better results in terms of bay response to events, but could not yield stable tidal components. The de-trending of tidal records before harmonic analysis was not specified in the earlier literature. Thuy et al. (2012), modified the method adopted in Hinwood & McLean (2001) but with a window length of 24.5h and examined two main (one diurnal and one semi-diurnal) tidal components through closure events of Avoca Lake tidal records without de-trending before harmonics analysis. This paper applies the 24.5hour moving window method with de-trending.

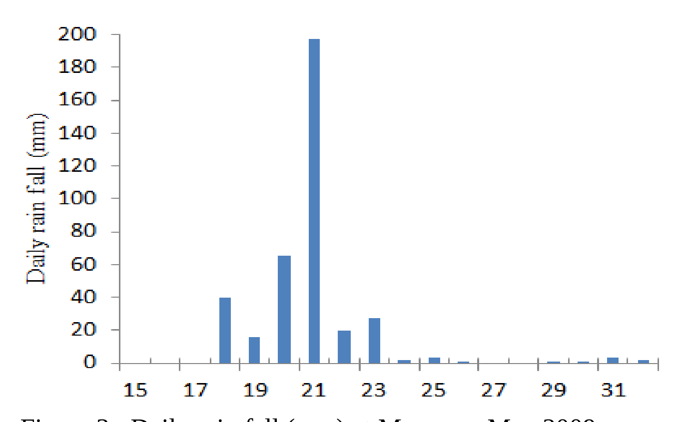


Figure 3: Daily rain fall (mm) at Myocum, May 2009.

Time series of hourly 24.5h moving averages are derived from

$$\overline{h_{24.5}}(t) = \frac{1}{24.5h}\int_{t-12.25h}^{t+12.25h} h(t')\,dt' \quad (1)$$

The corresponding standard deviations $Stdv_{24.5}$(t) are generated analogously.

Harmonic analysis can be applied directly to tidal records under steady, equilibrium circumstances, where the hydraulic response in general and the tidal response functions F_1 and F_2 in particular are constant. However, during extreme events the water levels increase radically due to rainfall and/or storm surges and later reduce after the event. In order to obtain meaningful F_1, F_2 results throughout a storm event the water levels are de-trended (or de-meaned) by subtracting $\overline{\eta_{24.5}}(t)$ before the harmonic analysis is applied to obtain one diurnal (24.5h) and one semi-diurnal (12.25h) amplitude [$R_1(t)$, $R_2(t)$] and their phases [$\varphi_1(t)$, $\varphi_2(t)$]. These parameters are evaluated every hour by stepping the 24.5h window forward. The ratio

between the bay tide amplitudes and the corresponding nearest ocean tide amplitude provides the gain $G_j(t)= R_{Rj}(t)/R_{oj}(t)$ and phase lags $\varphi_j(t) = \varphi_{Rj}(t) - \varphi_{Oj}(t)$, where "$_R$" denotes river and "o" denotes ocean, j=1, 2 with 1 for diurnal and 2 for semi-diurnal. The complex frequency response functions are correspondingly $F_j = G_j e^{-i\varphi_j}$.

The morpho-dynamic time scale T_{morph} can be determined by fitting suitable functions with asymptotic behavior of the form exp[$-t/T_{morph}$] to the shapes of $\overline{\eta_{24.5}}(t)$ and $Stdv_{24.5}(t)$ after the storms. A similar analysis was applied to closure events of Avoca Lake by Thuy et al. (2012). In the present study, functions of the form

$$G_j(t) = G_{jfinish} + \left[G_{jstart} - G_{jfinish}\right] e^{-(t-t_{start})/T_{morph}} \quad (2)$$

are fitted to the tidal gains as demonstrated in Figure 7.

4. Results and discussion

4.1 Mean and standard deviation

The hourly mean water level $\overline{\eta_{24.5}}(t)$ and standard deviation $Stdv_{24.5}(t)$ from a central, 24.5hour moving window analysis for ocean and Brunswick River are shown in Figure 4. $Stdv_O(t)$ shows that this event happened after the neap tide. Similar trends and magnitudes are observed for $Stdv_o(t)$ and $Stdv_R(t)$ with maximum $Stdv_o(t)$ being 0.6m at spring tide. The mean (24.5hour) river water level $\overline{\eta_{24.5}}_{-R}(t)$ increases and reaches a peak of 0.85m on 21/5, same day as the maximum rainfall. $\overline{\eta_{24.5}}_{-R}(t)$ then declines as the rain fall abades even though the highest waves persisted. This agrees with earlier observations (Hanslow et al, 1996) that the BHTG is not measurably influenced by wave setup. $\overline{\eta_{24.5}}_{-o}(t)$ shows a storm surge of the order of 0.35m on 22/5. However, the reason for the smaller peak seen on 19/5 in the $\overline{\eta_{24.5}}_{-o}(t)$ was not found. The difference between $\overline{\eta_{24.5}}_{-o}(t)$ and $\overline{\eta_{24.5}}_{-R}(t)$ has the same trend as $\overline{\eta_{24.5}}_{-R}(t)$ and has a peak of 0.55m. $\overline{\eta_{24.5}}_{-R}(t)$ returns to normal on 28/5, i.e., 6 days after the peak of the storm/rainfall event. It is clearly seen that both $\overline{\eta_{24.5}}_{-R}(t)$ and $Stdv_R(t)$ do not perform exponential trend approaching asymptote. Therefore they cannot be used for determination T_{morph}.

4.2 Diurnal and semi-diurnal harmonics

Results of harmonic analysis, i e, gain and phase lag for the two tidal components without de-trending is presented in Figure 5. The gain G_2 and the phase lag φ_2 of the semi-diurnal component is quite stable before and after thes torm, slightly oscillation during storm. No clear trend is observed to provide hint for interpretation of entrance morphology change. G_1 shows three peaks at almost 2, and φ_1 changes from lag to lead during the storm. This behavior is hard to explain.

The 24.5 hour moving window analysis of the diurnal and semi-diurnal tidal components starts with removal of $\overline{\eta_{24.5}}(t)$ from both ocean and river entrance data. After that the data from the considered event appear as in Figure 6.

Around the spring tides of 26/5, the mixed diurnal/semi-diurnal ocean tides have very uneven highs while the lows are very even. This may, if the entrance acts like a weir, generate large diurnal amplitudes corresponding to $G_1 = |F_1(t)| > 1$ in rivers and coastal lakes.

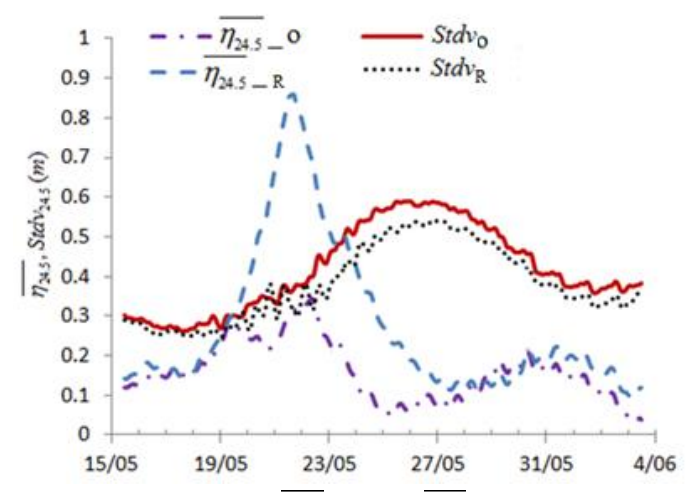


Figure 4: Results of $\overline{\eta_{24.5}}_{-o}(t)$, $\overline{\eta_{24.5}}_{-R}(t)$, $Stdv_O(t)$ and $Stdv_R(t)$ from 24.5hour moving window analysis for the May 2009 event at Brunswick Heads.

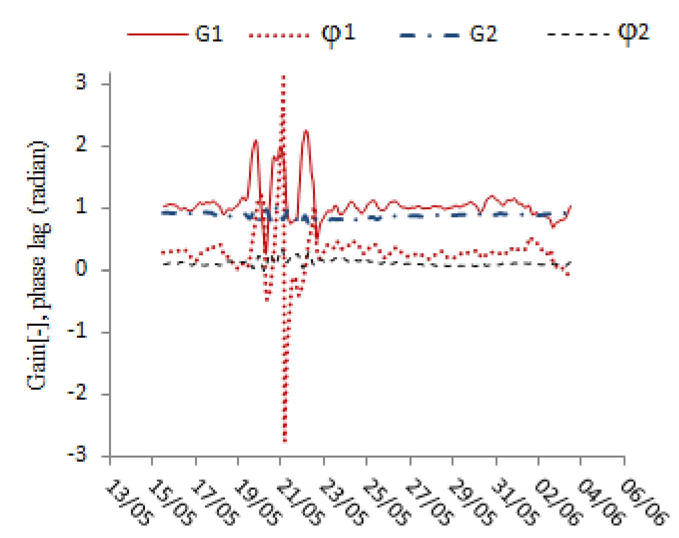


Figure 5: Gains and phase lags of the two tidal components obtained with a 24.5hour moving window without de-trending before doing harmonic analysis.

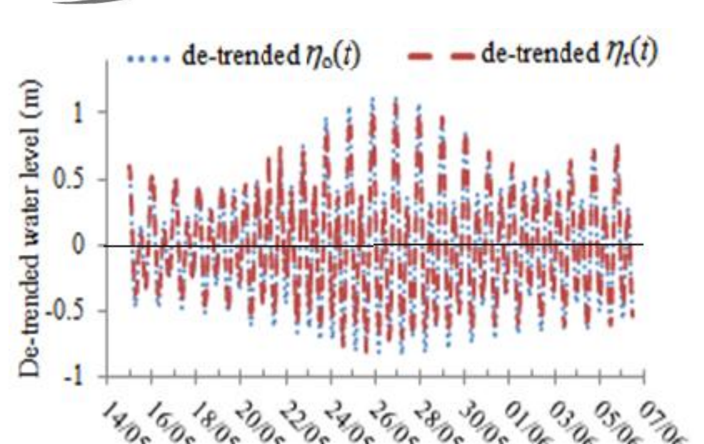


Figure 6: Ocean water levels at Coffs Harbour, and at the BHTG, after removal of the 24.5hour means.

While frequency response functions for a monochromatic system (purely diurnal or purely semidiurnal) will always be less than unity, bicromatic systems like the one considered here, Figure 7, often gives $|F| > 1$ for the subordinate (minor amplitude) component due to non linear effects. The difference between the results with and without de-trending, compare Figures 7 and 5. With de-trending G_2 shows a clear and intelligible trend. The exponential trend towards the asymptote after storm would be potential for extracting T_{morph}. G_1 shows a reduced number of peaks and values <1.5, φ_1 does not change from lag to lead even though its variation is still somewhat abrupt during the storm.

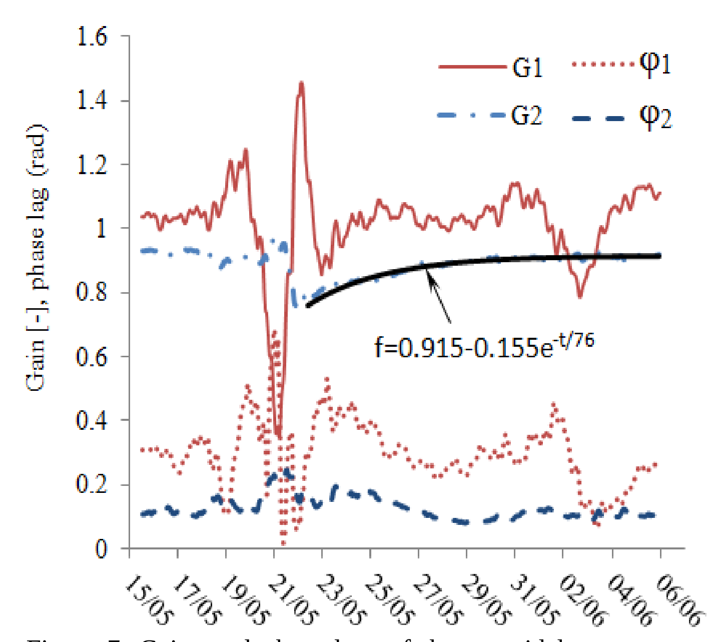


Figure 7: Gains and phase lags of the two tidal components obtained with a 24.5hour moving window on de-trended water levels together with fitting exponential function for G_2 to obtain T_{morph}=76h.

Figures 8 and 9 show the tracks of F_1 and F_2 in the complex plane through the event considered here. The gain $G_2 = |F_2|$ and the phase lag φ_2 of the semi-diurnal component (Figure7) increased on 21/5 during the same time when the mean water level reached its peak (rain fall was the heaviest), and both of them reduced on 22/5 when the mean water level reduced and then the G_2 increased towards its equilibrium value.

The increasing trend around 21/5 of G_2 is similar to the tidal analysis of Hinwood & McLean (2001) for Lake Conjola. However, they found that the phase lag at that time decreased. They explained that tidal response as a result of scour out the inlet, leading to a larger entrance cross section, which is hydraulically more efficient. The Brunswick River entrance phase lag increased at the same time as G_2 increased showing no clear increase in hydraulic efficiency during the event considered here. On the contrary perhaps, $|F_2|$ decreased at the time of peak fresh water flow Q_f. Such a behavior can be related to the non-linear nature of the bottom friction, which with a large Q_f gives increased bottom friction, hindering tidal response. This trend was confirmed by the tidal hydrodynamic modeling carried by Hinwood & McLean (2001).

The response of BHTG for the semi-diurnal component is close to perfect under normal conditions, viz., $G_2 = |F_2| = 0.91$ and φ_{R2} = 0.1radians (=6°). The response function F_2 makes a small loop during the storm when the system floods with a large Q_f and then comes back to the initial point when it recovers (Figure 9). The modest size of the loop shows that the Brunswick Entrance does not really change much, even under such a severe event due to protection from two breakwaters. F_1 shows nearly the same pattern but in larger scale with G_1>1 but more abrupt (Figure 8).

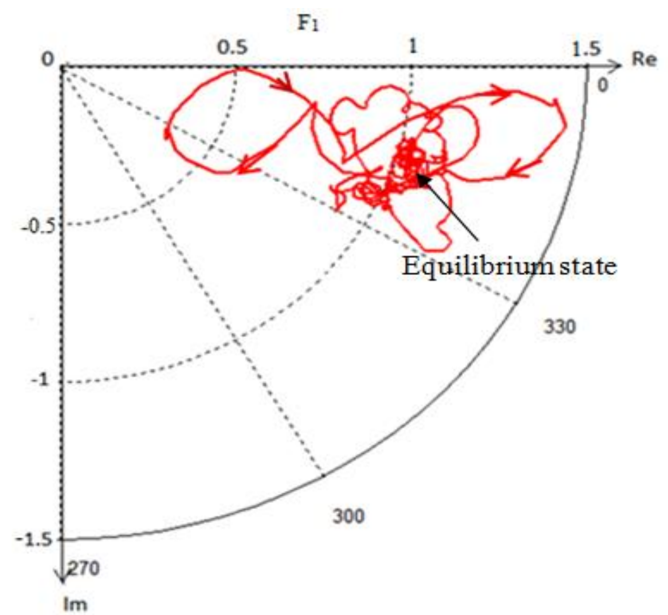


Figure 8: The tracks of subordinate diurnal constituent F_1 in the complex plane for May 2009 event. The track runs out of equilibrium at tight orbit $F_1(1.1, 20^o)$ to ca $(1.4, 5^o)$ corresponding to large wave then back to equilibrium after storm.

Figure 9: The tracks of dominant semi-diurnal component F_2 in the complex plane for May 2009 event. The tract shows modest variability and as expected remains smaller than unity. The track runs out of equilibrium at tight orbit $F_2(0.91, 6^o)$ corresponding to large wave then back to equilibrium after storm.

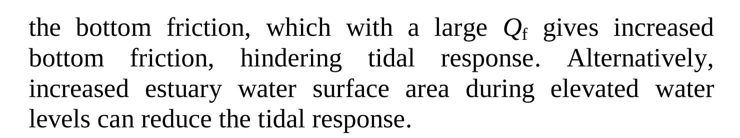
4.3 T_{morph} for the Brunswick River entrance

The hydraulic response data above show that the dominant semidiurnal component G_2 gets reduced during the storm event. The reason for it is that (a) rise of mean water level cause surface water area increase, and/or (b) river flow increase results in velocity increase, increasing the non-linear friction term in momentum equation. Then G_2 recovers more or less exponentially back to equilibrium state like before storm as indicated by Figure 7. Whether this is reflecting significant morphological change or “just hydraulics” as in the influence of Q_f on F_1, F_2, is not clear at present. Irrespective of the nature of change, the timescale, as indicated by the trend line equations in Figure 7, is around 76 hours.

5. Conclusions

We have demonstrated that morphodynamic and hydraulic parameters can be obtained from water surface measurements using the method of a 24.5 hour moving window. It can be applied not only for closure events but also for storm event and the accuracy of the results is improved by removal of $\overline{\eta_{24.5}}(t)$ from the water levels before harmonics analysis.

The Brunswick River entrance shows no clear increase in hydraulic efficiency during the event. The gain G_2 and the phase lag φ_2 increased on 21/5 during the same time when the mean water level reached its peak (rain fall was the heaviest), and both of them reduced on 22/5 when the mean water level reduced and then G_2 increased towards its equilibrium value (Figure 7). G_2 decreased at the time of peak fresh water flow Q_f. Such a behavior can be related to the non-linear nature of


the bottom friction, which with a large Q_f gives increased bottom friction, hindering tidal response. Alternatively, increased estuary water surface area during elevated water levels can reduce the tidal response.

Response functions of both tidal components show clear equilibrium states corresponding to tight orbits, around $(G_2, \varphi_2) = (0.91, 6^o)$ respectively $(G_1, \varphi_1) = (1.1, 20^o)$ under normal conditions. Similar pattern, of running out of equilibrium during the storm and then returning to the equilibrium point, is observed for both F_1 and F_2 but at different scales and manner. F_2 makes a small loop during the storm when the system floods with a large Q_f and when it recovers. The modest size of the loop shows that the Brunswick Entrance does not really change much, even under such a severe event with protection of two breakwaters.

The time scale by fitting G_2 during recovery process is around 76 hours. This may be a hydraulic time scale as in the influence of Q_f on F_1, F_2 via the non-linear friction term rather than reflecting significant morphological change.

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